Multifunctional Sensor for Monitoring of CO₂ Underground Storage by Comprehensive and Spatially Resolved Measuring of Gas Concentrations, Temperature and Structural Changes

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Abstract

One of the main unsolved issues of CCS is the comprehensive surveillance of CO₂ storage areas with reasonable effort and costs. This study presents an approach for distributed subsurface monitoring of gas storage areas. The concept combines different measurement technologies to one multifunctional sensor: membrane based measurement technology for in situ monitoring of gases in soil and fibre optical sensing of temperature and strain (as a measure for structural change). A test field of application-relevant dimensions is built up to validate and optimize the technology.

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1. Introduction

Worldwide CCS is estimated as one of the most promising technologies for greenhouse gas control and reduction. Basic political decisions to promote CCS are made, e.g., in Europe with Directive 2009/31/EC [1]. Now pilot facilities are built up and start operation. At this point a more profound discussion starts and – at least in Germany – hinders the advance of CCS. The crucial question is about the entire safety of storage areas. Residents are afraid and protest against nearby facilities, local politicians stop the projects.

The Directive 2009/31/EC demands: “The choice of monitoring technology shall be based on best practice available at the time of design. The following options shall be considered and used as appropriate: … technologies that can provide a wide areal spread in order to capture information on any
previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO₂ out of the storage complex.”

Fulfilling this demand on basis of established sensors and measurement techniques is difficult. Mechanically robust gas sensors are required which a) gather reliable information from large areas, b) work efficiently within the subsurface, c) are insensitive to changing phase saturations and d) show an acceptable response time. Conventional gas sensors can only be used for punctual or locally limited measurements (e.g., in combination with soil air probes or borehole probes), their application can cause structural influences (invasive application), and, to check its operational reliability or its sensitivity, typically a sensor has to be dismounted from the observation point.

In cooperation with MeGaSen (www.megasen.com, a start-up from UFZ), BAM carries out a research project to enhance and validate an innovative approach for a distributed subsurface monitoring of gas storage areas, with the focus on CCS. The novel sensor layout offers the characteristics for a considerable technological advance in this crucial field of operation. The sensor installation can be designed with respect to the task or problem and an in situ maintenance of the installed sensors is possible without their dismounting.

Key aspect of the research project is the first-time validation of the technology for spatially resolved gas detection in a relevant scale for application. For this purpose a 20 x 20 m² soil test field is build.

2. Concept of the Sensor Design

Basis of the sensor design is the combination of different technologies to one multifunctional sensor:

- Membrane based measurement technology for in situ monitoring of gases in soil [2] and
- Fibre optical sensing of temperature and strain (as a measure for structural change) [3].

The gas sensor is based on the selective permeation of gases through a membrane. The measuring method combines the gas specific diffusion rates through a membrane with Dalton’s law of partial pressures. It enables the calculation of gas concentrations based on the ideal gas law using measurements of pressure, time and temperature. The sensor is implemented in form of a flexible tube. The synthetic material allows a variable subsurface installation, e.g., in meander or network form. So far the gas concentration measurement is implemented for CO₂ and O₂, further gases should follow (e.g., methane, H₂S or H₂).

Glass fibre optical sensors use the effects of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) for spatially resolved measuring of temperature and strain. Distributed strain measurements can also be performed with polymer optical fibres using optical time-domain reflectometry (OTDR). Fibre optical measuring systems can be implemented with length up to several kilometres and spatial resolution in meter range. BAM develops, validates and uses such sensor systems in different areas of application, such as geotechnics, structural engineering, and physical protection.

Combining these two sensor types to a multifunctional sensor offers an innovative and promising approach for spatially resolved monitoring of large-scale areas. Using sensor data fusion enables in-depth analysis of soil processes and early detection of relevant changes. Both technologies offer advantageous specifications, which support and encourage their combination:

- Distributed, area-wide applicable measuring system with spatially resolution of all variables
- Scalable and adaptable form of application, depending on monitoring object and problem
- Non-invasive system (no influence on the monitoring object, due to permanent presence of the sensor in the ground)
- No sensitivity against electro-magnetic fields (e.g., lightning and high-voltage lines)
Applicable in explosive surroundings (no electrical components at the measuring locations)
- High thermal and chemical robustness
- Comparatively reasonable components

The structural combination is accomplished by linkage of the sensitive elements membrane sensor and optical fibre. For this purpose, geogrid materials (Fig. 1) could act as a carrier material with which BAM has various experience and successfully conducted several developments. Combined data analysis in form of data fusion should be investigated and further developed to attain synergy effects, increase the sensitivity and informational value, and address new fields of application. For instance, the combined analysis of gas concentration, temperature, and strain can enable an indication of very small crack formation and gas emission, with significant higher reliability compared to sole gas measurements.

Fig. 1. Geogrid materials with integrated fibre optical sensors.

3. Multifunctional Sensor for Underground Monitoring

3.1. Gas sensor

The novel gas sensor allows the direct, phase-independent measurement of different gases in fluids using a uniform measuring concept. The concept is based on the selective permeation of gases through a membrane balancing concentration differences at both faces of its wall. This gas-selective equilibration process can be analysed by the corresponding change of pressure within the tubular membrane. Hence the membrane itself acts as the sensory element, not as a phase separator but as a gas component-selective sensor.

The method allows a problem oriented design which enables spatially averaged measurements in line or matrix structure (Fig. 2), in contrast to conventional methods like soil gas sensors, borehole probes, or gas sampling with subsequent spectroscopy. Through this a highly efficient safety monitoring of potentially endangered areas becomes possible as well as long term measuring. Compared to conventional measuring, additional benefits of the method are the independency from the phase composition (aqueous
phase, gas phase) and its spatial distribution (saturation differences) [2, 4], as well as the possibility to calibrate the installed sensors without to dismount them from the soil enabling a reliable long-term observation of gases [5].

![Diagram of spatially distributed gas monitoring](image-url)

Fig. 2. Spatially distributed gas monitoring built up of several membrane sensors. The brown and yellow areas indicate CO$_2$ hotspots underground. The red and grey curves display the averaged measurements of the partial CO$_2$ pressure over x and y, respectively.

The method was evaluated in the laboratory resulting in a high accuracy for CO$_2$ analysis which depends strongly of the membrane material and the sensor geometry but behaves less correlated to the concentration [5, 6]. Hence, the technology is perfectly suitable to determine higher CO$_2$ concentrations (1 to 5 \%$_{vol}$) which are typical for soils and leakage affected regions.

In a first field experiment it was demonstrated that a single membrane based gas sensor enables to estimate the minimum affected area around a leakage [6]. This result could be of special interest for the surveillance of a pipeline.

3.2. Temperature and strain sensor

The distributed temperature and strain measurement by means of fibre-optical sensors is based on the effect of the stimulated Brillouin scattering (SBS) which uses the interaction between optical waves and sound waves. On basis of the typical Brillouin frequency shift, temperature and strain of a glass fibre can be determined [3, 7]. This measuring principle is used in various research projects at BAM and was realized within the scope of the project „Sensorbasierte Geotextile zur Deichertüchtigung“ (Sensor-based geotextiles for dike strengthening) in new form [8]. Fig. 3 and Fig. 4 show a distributed measurement for an exemplary strain profile. The visible movements of the spectra to higher frequency correspond to the strain measured by the fibre sensor (a frequency difference of 500 MHz corresponds to a strain of the fibre of 1\%) (Fig. 3).
3.3. Multifunctional sensor

The combination of both sensing methods allows the development of a measuring system with high novelty value. Both principles complement each other optimally through their specifications and application possibilities. In this study, for the first time a combined system is implemented for the distributed, spatially resolved measuring of gas concentrations, temperature and strain which allows a comprehensive underground monitoring. Main parts of the measuring system are the sensitive elements tube-shaped membrane and optical fibre which are joined to a multifunctional sensor structure. To capture
simultaneously the three measuring dimensions gas concentration, temperature and strain, the one membrane sensor is connected with two fibre sensors – one for the strain measurement and one for the temperature measurement.

Laboratory tests are performed to determine which type of fibre-optical sensors (fiberglass or polymer fibre) with which specifications are best suitable and whether the membrane sensor itself is capable to act as a carrier material for the sensor fibres or an additional carrier material (geotextiles or geogrid) is required. Former experiences hint that the membrane sensor itself made from a polydimethylsiloxane, (PDMS) membrane and a polyethylene (PE) membrane [5] could offer suitable characteristics for the direct fibre integration, like the adhesion to receive mechanical movement in the ground and the protection of the fibre sensor against fracture by avoidance of critical bending radii. However, issues regarding the material and production must be taken into account, such as the slide-steady integration of the fibres, the non-interference of their sensing characteristics and the production costs. In these regards the use of geotextiles offers an established and easy to handle alternative.

3.4. Expected Results

- The real-time analysis of the local concentration distribution within the soil will be demonstrated at field scale basing on an inversion of the analysed mean concentrations by the running gas sensor grid.
- An improvement of resolution of the gas measurement can be expected on account of the spatially highly resolved temperature information.
- Identification and differentiation of gas emission processes in the ground (e.g., soil respiration, seam fire, leakage) due to different dependencies on the temperature and soil structure, or a subsequent resulting temperature and tension signature.
- Significant gain in knowledge regarding advective gas movement within a soil, the emission behaviour of different soil structures, and dependencies between the features of the gas source (emission rate, shape) and gas movement.
- Additional gain in knowledge regarding the temperature distribution and soil structure changes as a result of sediment movements, settlement phenomena, rearrangement of the soil moisture, etc.
- In-situ calibration as demonstrated in [5] assures the long-term operability of the sensor and enables to observe the ageing behaviour of the membrane material.

Two immediate fields of application are:
- Landfills produce greenhouse gas and warmth. The combination of both measurement methods should allow a potent landfill monitoring by containment of chemical active areas and leakages.
- Underground storage of CO₂ as well as extraction and production of gases from geological areas can lead to mechanical changes of the deck rock (lowering / elevation) with which a regional tension field is build up. Thus gas-leading gaps can be induced which cause local ground structure changes. The simultaneous measurement of spatially resolved gas concentrations and strain allows the development of an efficient early warning system. Because the underground conversion of organic substances correlates directly with the temperature, the local appearance of non-correlated CO₂ concentrations points to the influx of CCS-CO₂.

4. Test Field for Sensor Validation

The validation, optimization, and practical demonstration of the overall system are carried out in a test field on the BAM Test Site Technical Safety (BAM TTS) [9]. The BAM TTS disposes state-of-the-art
facilities and offers excellent capabilities for the investigation and testing of various safety issues and solutions. Since 2010 on the BAM TTS a test field for the validation of distributed measuring systems is build up which is already used for the investigation of fibre-optical sensors. In this scope a test field of 20 x 20 m² is under construction to validate and enhance the combined system in application-relevant scale. The sensor installation should be applied in several depth of the test field, in one level over the complete field area and in the other levels at least partially. An exact draft for the test field is displayed in Fig. 5. For the simulation of gas emissions an injection system with about 100 gas injection points is implemented in the way that quantitatively and spatially defined gas release can be applied, reproducibly. A systematic variation of parameters, such as position dependent gas injection, soil temperature (through heating elements and shielding of the solar irradiation), or mechanical impact (through lifting bags) which will be repeated for various weather and ambient conditions (irrigation, wind, soil water content, etc.) allows a comprehensive investigation and validation of the sensor system.

The equipment for system operation and data acquisition, including industrial PC is located centrally on the surface of the test field, protected against weather and unauthorized access. Throughout the BAM TTS infrastructure for power supply and network access is available, so that a continuous operation and online data transfer are assured.

Fig. 5. Sketch of the 20 x 20 m² large test field consisting of three sensor levels, a gas-injection system, lifting bags to simulate structural changes, heating elements to induce a local change in temperature, and temperature and soil moisture sensors.

5. Summary and Outlook

An innovative approach was introduced for a multifunctional sensor to investigate subsurface processes. The combination of the measurands CO₂ concentration, temperature and strain qualifies the sensor particularly for safety application in CCS storage areas. Two measuring principles, the permeation-selective membrane and the stimulated Brillouin scattering (SBS) in fibre optics complement each other
to a highly sophisticated sensing concept. At BAM a project is carried out in which scope a test field in application-relevant dimensions is build up. Gas emission processes can be simulated as well as temperature and mechanical impact to validate and enhance the multifunctional sensor.

Moreover, intelligent algorithms are in development for real-time safety assessment based on data fusion and combined analysis of the three measurands. It is objective to qualify the overall system for achieving a gain in knowledge of phenomena within the subsurface, particularly in regard to gas release processes. Future tasks are the long-term validation of the sensing characteristics such as robustness, sensitivity, reliability and the enhancement to measure other relevant gases such as methane or H2S.

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